A Broad-Band Glass-to-Metal Coaxial Vacuum Seal*

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Summary—**The design procedure for a broad-band glass-to-metal seal is described, and experimental results are presented for a structure examined over the frequency range of 100 to 11,000 Mc. The seal described is capable of operating at bakeout temperatures as high as 450°C, with higher temperatures being attainable by the use of other materials.**

INTRODUCTION

THE fabrication of electron beam devices has led to the requirement for a glass-to-metal vacuum seal in a coaxial transmission system possessing a low standing wave ratio over a wide frequency range. Of the several configurations containing discontinuities[1] the majority involve an abrupt transition with its accompanying bandwidth limitations. It is the purpose of this paper to describe the design and experimental characteristics of a broad-band glass-to-metal vacuum seal developed in this laboratory.

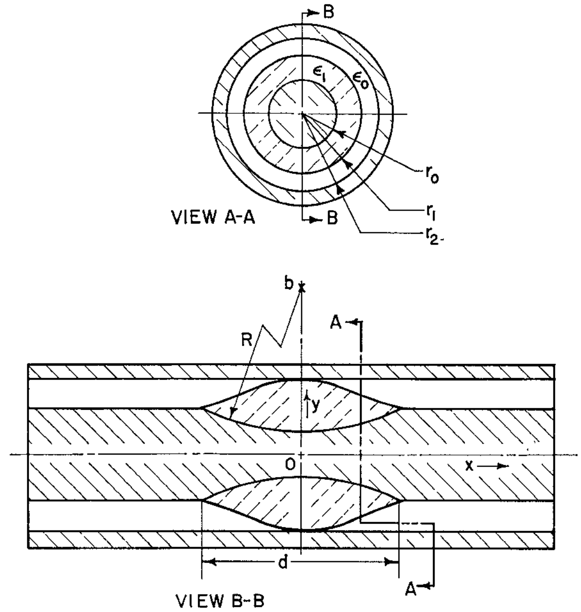
MATHEMATICAL ANALYSIS

The basic geometry of the transmission system consists of a coaxial line constructed from Kovar tubing and round stock. The inner conductor is undercut along a circular arc of prescribed radius in the region where the glass-to-metal seal is to be obtained, as shown in Fig. 1.

Since only the TEM mode is presumed to exist in the lossless coaxial line, the characteristic impedance of the air-glass dielectric region (such as view A-A) of Fig. 1 can be computed by means of[2,3]

$$Z_0 = \sqrt{\frac{L}{C}}, \tag{1}$$

where L = inductance per unit length of the transmission line in henry per meter, and C = capacitance per unit length of the transmission line in farad per meter. Subject to the assumption that the permeability of the glass is the same as that of air, the inductance per unit length is found to be[2]



b = center of undercut circle
R = radius of undercut circle
d = length of center-conductor undercut section
r_0 = outside radius of inner conductor
r_1 = radius of glass seal
r_2 = inside radius of outer conductor
ϵ_0 = free-space permittivity
ϵ_1 = permittivity of glass

Fig. 1—Geometry of coaxial transmission system.

$$L = 2\cdot 10^{-7} \ln\left(\frac{r_2}{r_0}\right) \text{ henry per meter,} \tag{2}$$

where $\ln (r_2/r_0)$ designates the natural logarithm of the ratio of radii defined in Fig. 1. The capacitance per unit length can be determined for a typical transverse plane containing the two types of dielectric by noting first that the "RF voltage" V, in that plane, is equal to

$$V = \int_{r_0}^{r_1} \frac{Qdr}{2\pi\epsilon_1 r} + \int_{r_1}^{r_2} \frac{Qdr}{2\pi\epsilon_0 r}. \tag{3}$$

It follows that

$$C = \frac{2\pi k\epsilon_0}{\ln\left(\frac{r_1}{r_0}\right) + k \ln\left(\frac{r_2}{r_1}\right)} \tag{4}$$

where Q designates the charge per unit length and k denotes the relative dielectric constant of the glass seal.

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[1] G. L. Ragan, "Microwave Transmission Circuits," M.I.T. Rad. Lab. Ser., McGraw-Hill Book Co., Inc., New York, N. Y., vol. 9; 1948.
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[3] S. Ramo and J. R. Whinnery, "Fields and Waves in Modern Radio," John Wiley and Sons, Inc., New York, N. Y., 2nd ed.; 1953.

Upon substituting (2) and (4) into (1), the characteristic impedance becomes

$$Z_0 = 60 \sqrt{\ln\left(\frac{r_2}{r_0}\right)\left[\ln\left(\frac{r_2}{r_1}\right) + \frac{1}{k}\ln\left(\frac{r_1}{r_0}\right)\right]} \text{ ohms.} \quad (5)$$

Since the inside diameter of the outer conductor is held constant over the entire length of the line, the basic problem is reduced to the determination of the manner in which the radius of the glass must vary with the axial dimension x, for a specified variation of the center conductor, to maintain the impedance invariant[4] when only TEM waves are presumed to exist.

The investigation is facilitated by observing that (5) can be written

$$\ln\left(\frac{r_2}{r_1}\right) = \frac{k}{k-1}\left[\frac{(Z_0/60)^2}{\ln(r_2/r_0)} - \frac{\ln(r_2/r_0)}{k}\right]. \quad (6)$$

This relation has been employed to obtain the general design curves presented in Fig. 2. Using an assumed characteristic impedance of 50 ohms, the ratio (r_2/r_1) is plotted vs the independent variable (r_2/r_0) over the range of dielectric constant values typically found in the vacuum sealing glasses. Thus, upon selecting a specific value of (r_2/r_0), an associated value of (r_2/r_1) which yields an invariant impedance may be read from the curves. It is therefore possible to select a particular variation of the radius of the center conductor as a function of x and find the required variation of the glass.

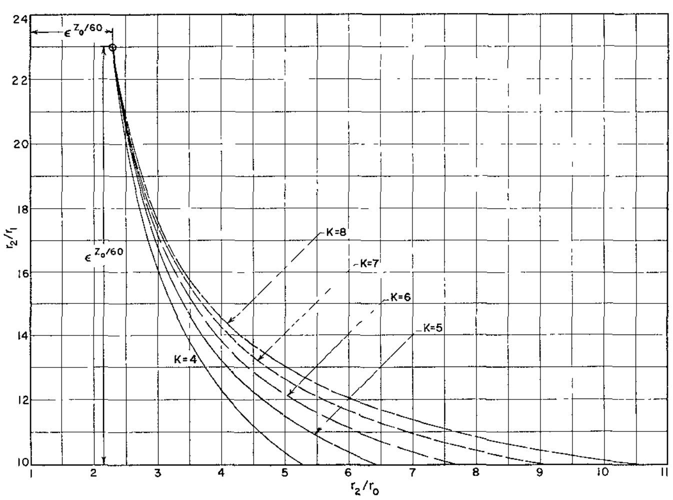

Fig. 2—Universal design curves for a glass-to-metal seal having a prescribed dielectric constant in a transmission line of 50 ohms characteristic impedance.

[4] It is assumed that the change of radii will be sufficiently gradual so as to avoid the generation of longitudinal field components.

Fabrication Procedure

The variation of the radius of the glass as a function of x, which has been experimentally investigated at this laboratory, is the one for which the radius of the center conductor follows a segment of a circle as shown in Fig. 1. If the center of this circle of radius R is chosen at b as indicated, the radial dependence of the center conductor upon the axial coordinate is given by

$$r_0(x) = b \mp \sqrt{R^2 - x^2} \left(|x| \leqq \frac{d}{2} \right), \quad (7)$$

where the upper double sign holds for $y>0$, and the lower sign applies when $y<0$. This relation may be used in conjunction with the design curves of Fig. 2, and the specific numerical data given below, to obtain the desired shape of the glass seal.

Since the inside radius of standard $\frac{1}{8}$-inch Kovar tubing has a fixed value of

$$r_2 = 0.054 \text{ inch,}$$

it follows from (5) that the radius r_0 becomes, for a 50-ohm characteristic impedance in air,

$$r_0(x) = 0.02345 \text{ inch} \left(|x| \geqq \frac{d}{2} \right).$$

This radius can be accurately machined by centerless grinding standard 1/16-inch Kovar round stock. Similarly, application of (5) to the region containing only the glass, whose dielectric constant is approximately 5, yields for the 50-ohm impedance condition

$$r_0(x) = 0.00836 \text{ inch} \qquad (x = 0).$$

It may readily be shown from elementary mathematics that the radius R of the "undercut circle" depicted in Fig. 1 is given by

$$R = \frac{h}{2}\left[1 + \left(\frac{d}{2h}\right)^2\right], \quad (8)$$

where d is the length of the undercut measured parallel to the axis of the center conductor, and

$$h = r_0\left(\frac{d}{2}\right) - r_0(0). \quad (9)$$

In (9) the quantity $r_0(d/2)$ designates the radius of the center conductor at $x=d/2$, while $r_0(0)$ designates its radius at $x=0$. Using the previously computed values of $r_0(x)$ in conjunction with (9) it follows that

$$h = 0.01509 \text{ inch.}$$

This quantity is used in conjunction with (8) to obtain a radius R of 2.078 inch, corresponding to a length of undercut d equal to 0.500 inch. The desired radius may easily be obtained to an accuracy of ± 0.001 inch. The center conductor is then ground to the desired radius of undercut by a surface grinder while the Kovar stock is rotating in a cylindrical grinding attachment.

Having thus established numerical values for the radial dimensions of the coaxial transmission system, as well as one attainable dependency upon x of the center conductor radius, it is now possible to plot the required variation of the glass radius necessary to maintain a constant impedance. Using the graphs of Fig. 2 for the case of a dielectric constant equal to 5, a curve of this type is presented in Fig. 3 for a center conductor containing a 0.500-inch length d of undercut. Near $x=0$ the curve is very nearly flat and exhibits slight rounding as the steep portion is approached. At large values of x the asymptotic behavior of the function is evident.

The mechanical preparation of the outer Kovar tubing is completed by enlarging its inside diameter slightly over a distance of approximately $\frac{1}{8}$ inch from each end. This operation simplifies the insertion of the glassed center conductor and also improves the impedance match in the connector-to-air dielectric region by avoiding abrupt discontinuities.

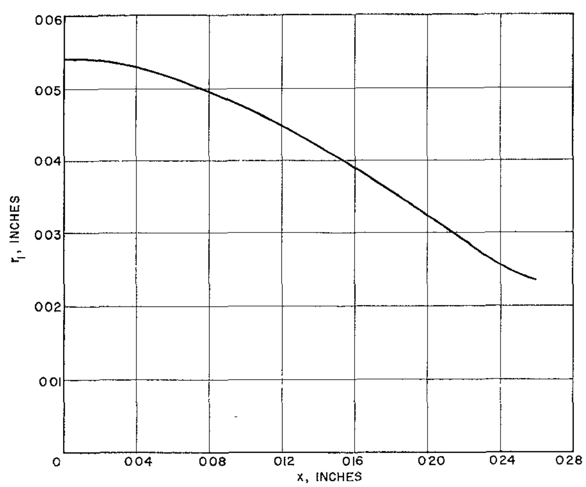

Fig. 3—Variation of glass seal necessary to maintain constant impedance for: $k=5$, $d=0.500$ inch, $r_2=0.054$ inch, $r_0(0)=0.00836$ inch, $r_0(d/2)=0.02345$ inch.

In order to insure the maintenance of vacuum by the 7052 Kovar sealing glass, and to minimize the possibility of reflection of the RF wave, it is essential to avoid the formation of bubbles in the glass. This detrimental condition can be circumvented by observing the customary hydrogen or vacuum firing procedure, and the preheating cycle[5] immediately prior to sealing, which serves to outgas the Kovar tubing. Moreover, the oxide coating necessary to achieve a proper glass-to-metal bond is simultaneously obtained by this process.

The configuration of the glass contour in the glass-air transition region of the dielectric is formed to the general shape of the curve shown in Fig. 3. It is essential to exercise care to insure that excess glass is present on all surfaces. The glass bead is then ground to the desired contour using a $\frac{3}{4}$-inch-diameter grinding wheel, while the entire seal and center conductor is rotating in a glass lathe. The diameter of the center portion of the glass bead is ground until a slip fit is obtained in the Kovar tubing.

[5] The temperature is raised approximately 200°C above the glass-working temperature with the sealing torch.

The positioning of the center conductor and seal within the Kovar tubing is accomplished by appropriate jigging. The temperature is brought slowly up to the annealing point of the glass with a carbon flame and then quickly elevated to the sealing temperature of the glass for 15 to 20 seconds. The outline of the bead in the vicinity of the tubing will soften and tend to contract to a spherical shape, thereby enlarging the surface of contact with the tubing. In addition to aiding the maintenance of a good vacuum, this configuration has the desired form required to maintain the characteristic impedance constant. In view of the temperature gradient which exists between the center and outer conductors as a result of the short heating time, glass flow along the center conductor is minimized.

Experimental Results

The small size of the coaxial tubing described here was selected to minimize the possibility of exciting higher mode fields in the transmission system. Experimental observations reveal that the seals are capable of maintaining a vacuum well within the range of 10^{-8} to 10^{-7} mm Hg.

Several glass-to-metal seals were constructed and measured over the frequency ranges of 100 to 1000 Mc and 2000 to 11,000 Mc. In the lower of these two ranges, the seal was inserted in a section of coaxial transmission line terminated with a type-N connector at each end. Using the design procedure described above, two such seals were constructed, one with an undercut d equal to 0.500 inch and the other of 0.750 inch. It was found that the average VSWR for both seals was approximately 1.1, with minimum and maximum standing-wave ratios of 1.05 and 1.19, respectively.

Measurements in the frequency range of 2000 to 11,000 Mc are somewhat more difficult to carry out since reflections from the type-N connectors have been found to be undesirably large. The test apparatus involved the construction of a 0.025-inch-wide slot in the coaxial transmission system containing the glass bead. A 9.5-inch-length taper load was inserted in the transmission system immediately following the glass bead. A very gradual taper was achieved by wrapping the center conductor with cotton or nylon thread, and subsequently coating it with several applications of acquadag. Experimental observations made on a transmission system containing the load alone revealed that the standing-wave ratio could be kept to approximately 1.06 over the desired frequency range.

The entire bead-and-load coaxial system was attached to a Hewlett-Packard universal probe carriage, with appropriate mechanical supports being constructed to minimize transverse motion of the probe. Since the probe diameter of approximately 0.020 inch was used (thereby allowing a clearance of only 0.002 inch between the probe and slot), precise centering of the probe in the slot was accomplished by observing the standing-wave indicator as the probe was moved along the length of the slot.

Aside from the difficulties associated with variable probe-to-slot coupling,[6] slope effect,[7] radiation from the slot, minimum probe penetration, and proper probe tuning[8] must be carefully considered in order to interpret the data. Upon following the recommended procedures, the results for a glass seal having a one-half-inch length of undercut are plotted in Fig. 4. A second seal of identical design was constructed to determine the degree to which the characteristics could be duplicated. It was found that substantially the same SWR dependence upon frequency was obtained. From these observations it appears that the reflections produced by the glass seal alone lead to a SWR of less than 1.3 over the range of frequencies examined.

[6] E. L. Ginzton, "Microwave Measurements," McGraw-Hill Book Co., Inc., New York, N. Y.; 1957.
[7] C. G. Montgomery, "Technique of Microwave Measurements," M.I.T. Rad. Lab. Ser., McGraw-Hill Book Co., Inc., New York, N. Y., vol. 11; 1947.
[8] J. I. Caicoya, "Tuning a probe in a slotted line," PROC. IRE, vol. 46, pp. 787–788; April, 1958.

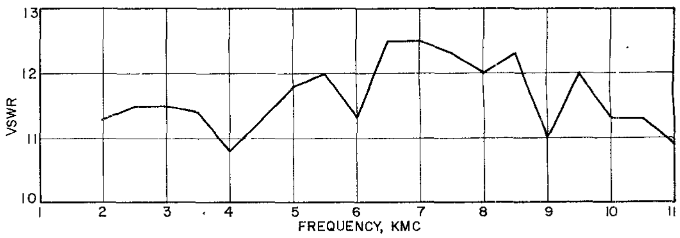

Fig. 4—Experimental results for the glass-to-metal seal.

Conclusions

The design procedure developed in this paper leads to the prediction of the shape of the glass seal required to maintain the characteristic impedance of a TEM wave invariant. The coaxial glass-to-metal seal described here may be employed in the construction of electron beam devices requiring bakeout temperatures as high as 450°C. It should also be possible to replace the Kovar metal with molybdenum and still achieve the same bakeout temperature, while also obtaining a nonmagnetic seal. Moreover, if 1720 or 1723 (aluminum silicate) glass is used in conjunction with molybdenum, a nonmagnetic seal having a bakeout temperature as high as 700°C can be attained.

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